DYNAMICAL AND EVOLUTIONARY CONSTRAINTS
ON THE NATURE AND ORIGIN OF HYPERVELOCITY STARS

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ABSTRACT

In recent years several hypervelocity stars (HVSs) have been observed in the halo of our Galaxy. Such stars are thought to be ejected through dynamical interactions near the massive black hole (MBH) in the Galactic center. Three scenarios have been suggested for their ejection; binary disruption by a MBH, scattering by inspiraling IMBH and scattering by stellar BHs close to MBH. These scenarios involve different stellar populations in the Galactic center. Here we use observations of the Galactic center stellar population together with dynamical and evolutionary arguments to obtain strong constraints on the nature and origin of HVSs. We show that the IMBH inspiral scenario requires too many ($\mathcal{O}(10^3)$) main sequence B stars to exist close to the MBH (< 0.01 pc) at the time of inspiral, where current observations show $\mathcal{O}(10)$ such stars. Scattering by SBHs also require too many B stars to be observed in the GC, but it may contribute a small fraction of the currently observed HVSs. The binary disruption scenario is still consistent with current observations. In addition it is shown that recently suggested signatures for HVSs origin such as hypervelocity binaries and slow rotating HVSs are much weaker than suggested and require too large statistics. In addition, we show that due to the conditions close to the MBH most binary star systems are not expected to survive for long in this region. Consequently, unique stellar populations that require long evolution in binaries are not expected to be ejected as HVSs in the BHs scattering mechanisms (this may also be related to to the recently observed asymmetry in the velocity distribution of HVSs).

Subject headings: black hole physics — galaxies: nuclei — stars: kinematics

1. INTRODUCTION

In recent years several hypervelocity stars (HVSs) have been observed in the halo of our Galaxy, some of them unbound to the Galaxy (Brown et al. 2007b). Most of the observed HVSs are B-type stars (Brown et al. 2005, 2006a,b, 2007a,b; Edelmann et al. 2005), implying a Galactic population of 96 ± 10 such unbound HVSs (closer than $\sim 120\,kpc$ to the Galactic center (GC); Brown et al. 2007b). Given the color selection of the targeted survey for these stars (Brown et al. 2006a), such stars could be either main sequence (MS; or blue straggler) B stars or hot blue horizontal branch (BHB) stars. Only four of the observed B type stars have stellar type identification, and were found to be B type MS stars (Edelmann et al. 2005; Fuentes et al. 2006; Przyble et al. 2008; Lopez-Morales & Bonanos 2008). In addition a single subdwarf O HVS has been observed (Hirsch et al. 2005). More recently a new HVSs survey of A type stars have detected additional HVSs (Brown et al. 2008). We also note that more HVSs may be detected in the future in M31 (Sherwin et al. 2007) and other galaxies.

Extreme velocities as found for these stars most likely suggest a dynamical origin from an interaction with the massive black hole (MBH) in the GC. Several scenarios have been suggested for ejection of HVSs; a disruption of a stellar binary by the MBH in the GC (Hills 1988; Yu & Tremaine 2003; Perets et al. 2007; hereafter the binary disruption scenario), an interaction of a single star with an intermediate mass black hole (IMBH) which inspirals to the GC (Hansen & Milosavljević

2003; Yu & Tremaine 2003; Levin 2006; hereafter the IMBH inspiral scenario), or interaction with stellar black holes (SBHs) in the GC (Yu & Tremaine 2003; Miralda-Escudé & Gould 2000; O'Leary & Loeb 2007; hereafter the SBHs kicks scenario). The later two scenarios scatter HVSs mostly from regions very close to the MBH (< 0.01 pc) where as the binary disruption scenario mostly eject HVSs that evolved in binaries much further from the MBH ($\gtrsim 2$ pc). The IMBH inspiral scenario is a discrete event, which does not occur continuously (although a sequence of several IMBH inspirals may eject HVSs semi-continuously; Löckmann & Baumgardt 2007) where the binary disruption or SBHs kicks are continuous processes leading to a constant rate of HVSs ejection. The different stellar populations involved in the different scenarios, the importance of binarity in the binary disruption scenario and the dynamical history of HVSs ejection could thus help to constrain the nature and origin of HVSs.

Recently several methods were suggested for discriminating between the HVSs ejection mechanisms. These include the differences in the velocity and directional distribution of HVSs (Levin 2006; Baumgardt et al. 2006; Sesana et al. 2007a), the binarity of HVSs (Lu et al. 2007) and the rotational velocities of HVSs (Hansen 2007). Brown et al. (2007b), Svensson et al. (2007) and Kenyon et al. (2008) discussed the propagation of observed HVSs and the asymmetric distribution of ingoing and outgoing HVSs (with negative and positive radial velocities, respectively, in Galactocentric coordinates) in regard to their nature (MS B stars or hot BHB stars).

Here we use the current observations of HVSs, observations of the stellar population in the GC, and dynamical

arguments to further constrain the possible scenarios for the origin of HVSs. We show that the population of B type MS stars required by the IMBH inspiral scenario and the SBHs kicks scenario are too large to be consistent with current observations. We then discuss some unique stellar populations that require long evolution in binaries, and suggest that they are not likely to be ejected as HVSs in the SBHs kicks or IMBH inspiral scenarios, since their binary progenitors are not likely to survive in the harsh environment close to the MBH. We also discuss the implications of the short survival time of binaries to the distribution of HVSs rotational velocities and show that these are not likely to serve as good discriminators for HVSs origin. Finally we shortly discuss how these arguments may be related to the recently observed asymmetric velocity distribution of observed HVSs (Brown et al. 2007b).

2. CONSTRAINTS FROM THE YOUNG STELLAR POPULATION IN THE GALACTIC CENTER

In each of the HVSs ejection scenarios the unbound HVSs reflect only a fraction of the total number of stars ejected from the GC. Many more stars are ejected at lower velocities, but high enough to escape the close environment of the MBH. Given the inferred number of B type HVSs from current observations one can obtain the total number of such ejected stars. Therefore we can infer the number of such stars that have existed in the appropriate environment of the GC during the time period of HVSs ejection. In the following we consider the constraints on the HVSs scenarios suggested by such considerations. We assume a total number of unbound HVSs of ~ 100 (Brown et al. 2007b). This is probably only a lower limit for the total number of HVSs, since many of them might have had higher velocities and propagated beyond the $\sim 120\,kpc$ currently observed, therefore the constraints suggested here might be more stringent .

2.1. *The IMBH inspiral scenario*

In the IMBH inspiral scenario (Hansen & Milosavljević 2003; Yu & Tremaine 2003), an IMBH inspirals to the Galactic center through dynamical interactions with stars. In the late stages of the inspiral, when the IMBH is already close to the MBH in the GC (< 0.01 pc or even less, depending on the IMBH mass), it may closely interact with stars and scatter them at very high velocities, thus producing HVSs (Levin 2006; Baumgardt et al. 2006; Löckmann & Baumgardt 2007; Sesana et al. 2007b). Consequently the population of HVSs ejected by an IMBH in the GC should be strongly correlated with the stellar population in the central 0.01 pc of the GC[1]. In this scenario the stellar type of the stars (and hence their mass) only negligibly affect the possibility of their ejection as HVSs. Therefore any star in the close region of the MBH may become a HVS in this case.

Results of N-body simulations (Baumgardt et al. 2006; Löckmann & Baumgardt 2007; Sesana et al. 2007b) show that only a fraction of the stars are ejected as HVSs, and most are ejected at lower velocities. Sesana et al. (2007b) find a total number of 500 (2500) HVSs ejected for an IMBH mass of $\sim 5 \times 10^3\,M_\odot (\sim 1.5 \times 10^4\,M_\odot)$. They find the total number of stars ejected during the inspiral to be about 10^4 (3.5×10^4). These numbers indicate that a fraction of $f_{HVS} \sim 0.05$ (0.07) of all ejected stars during the IMBH inspiral are HVSs. Current observations infer ~ 100 unbound B-type HVSs exist in the galaxy, and therefore $\sim 100/f_{HVS} \sim 2000$ (1400) B-type stars must have been existed at distance of 0.001 (0.01) pc from the MBH during the short time of IMBH inspiral. Current observations show ~ 1 (30) B-type stars at 0.001 (0.01) pc from the MBH ((Eisenhauer et al. 2005; Ghez et al. 2005); less luminous B-type stars might be missed so this could get a factor of $3 - 8$ times larger[2]. One may suggest that the stellar population in the GC at the time of inspiral (up to $\sim 10^8$yrs ago) was significantly different than currently observed, however the possibility of so many B-type stars existing in this small region of the GC is highly unlikely, and would require a yet unknown process for producing such overabundance of B-type stars. Given our theoretical understanding of this process, the current observations of the GC and the inferred number of HVSs, the IMBH inspiral scenario is unlikely to be the main origin for the ejection of currently observed HVSs.

2.2. *The SBHs kicks scenario*

In the SBHs kicks scenario (Miralda-Escudé & Gould 2000; O'Leary & Loeb 2007), SBHs in the close environment of the MBH (mostly < 0.01 pc or even < 0.001 pc; O'Leary & Loeb (2007)) strongly interact with stars and scatter them at high velocities thus producing HVSs. Consequently, and similar to the IMBH scenario, the population of HVSs ejected by an IMBH in the GC should be strongly correlated with the stellar population in the central 0.01 pc of the GC. In this scenario the stellar type of the stars (and hence their mass) affects the possibility of their ejection as HVSs, but not strongly for the B MS stars of $3 - 4M_\odot$ currently observed.

Results of analytic calculations by O'Leary & Loeb (2007) indicate that only a fraction of the stars are ejected as HVSs, and most are ejected at lower velocities. They find that the ejection rate of stars at lower velocities than required for HVSs ($\lesssim 800km\,s^{-1}$) goes like $(v_{ej}/800\,km\,s^{-1})^{-2.5}$. For the 100 unbound HVSs inferred from observations about $\sim 100 \times (100/800)^{-2.5} \simeq 1.8 \times 10^4$ B type stars have been ejected from the central 0.01 pc with $> 100\,km\,s^{-1}$, i. e. for the lifetime

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[1] One could suggest that the ejected stars do not belong to the cusp population near the MBH, but have inspiralled in the cluster accompanying the IMBH, and have been scattered during the inspiral. However, simulations of such scenario show that the young stars are stripped from the cluster much before the IMBH reaches the central 0.01 pc (see e.g. Levin et al. 2005; Berukoff & Hansen 2006, see also observational evidence against the IMBH inspiral origin for the young stars in the GC Paumard et al. 2006) from which region HVSs can be ejected in this scenario.

[2] Assuming a present day mass function, and assuming the B stars to have masses between $3 - 15\,M_\odot$ the relative fractions of the observed (more luminous) B stars in the overall population of B stars can be estimated. The fraction of such stars f_{4-15} or f_{5-15} with masses between $4\,M_\odot < m < 15\,m_\odot$ or $5\,M_\odot < m < 15\,m_\odot$, respectively, are $f_{4-15} = 0.31$ and $f_{5-15} = 0.13$, i.e. up to $\sim 3-8$ times more B stars than observed (with lower masses) could be missed in these regions. In these calculations we assumed star formation at a constant rate with a Miller-Scalo IMF (Miller & Scalo 1979), and use a stellar population synthesis code (Sternberg et al. 2003) with the Geneva stellar evolution tracks (Schaller et al. 1992) to estimate that the present day number fraction of stars in the S-star mass range. Using an initial mass function instead gives a smaller factor of only $2 - 3$ times undetected B stars.

of such $3-4\,M_\odot$ stars, a star formation rate of at least $\sim 2 \times 10^4/2 \times 10^8 = 10^{-4}$ B stars per year is required. Given that most of the stars are not scattered outside the GC region, this is only a lower limit on the required star formation rate, and at least as many stars should have been left over in this region.

It is unlikely that regular star formation could have formed such stars so close to the MBH, given the tidal forces in this region (that would disrupt a progenitor molecular cloud). These stars might have formed continuously through a fragmentation of a gaseous disk, although so close to the MBH even such star formation would most likely be prohibited or be inefficient given the required Toomre criteria in this region (Levin 2007). Nevertheless, these stars could have formed at some larger distance such as the young stars observed at < 0.5 pc scale stellar disk in the GC (Paumard et al. 2006) and continuously migrated close to the MBH (Levin 2007). Such scenario would require the star formation rate at this region (most likely < 0.5 pc) to be $> 10^{-4}\,yr^{-1}$, and would also require an efficient mechanism for transferring a large fraction of these formed stars to the central 0.01 pc at short times. The relaxation time in the GC is much longer than the lifetime of such stars and therefore some other migration mechanism would be required (e.g. migration in a gaseous disk; Levin 2007). The central region of the GC probably contains $\lesssim 5 \times 10^2$ B type stars such similar to the observed HVSs (Eisenhauer, F.; private communication (2006)), and therefore implies a star formation rate of $< 5 \times 10^2/2 \times 10^8 = 2.5 \times 10^{-6}$ such B stars per year. This rate is much smaller than the minimally required rate of $\sim 10^{-4}\,yr^{-1}$ we found above for explaining the inferred number of HVSs in this scenario. More simply put we would have expected to observe $\sim 10^4$ B stars in the GC region where only ~ 500 are observed (or even less in the central 0.01 pc), suggesting that this scenario is unlikely to be the main origin for the ejection of currently observed HVSs, although it could explain a fraction of them.

2.3. *The binary disruption scenario*

In the binary disruption scenario (Hills 1988) binaries are disrupted by the MBH in the GC if they come closer than the tidal radius. One star is captured by the MBH where the other is ejected at high velocity thus producing HVSs. The fraction of ejected stars with velocities lower than those of HVSs is strongly dependent on the the semi-major axis distribution of the binaries (where higher velocity stars are ejected from disruption of closer binaries (Hills 1991; Bromley et al. 2006)) which is unknown in the GC. The velocity of an ejected star was found in numerical simulations Hills (1988); Bromley et al. (2006) to scale as

$$v_{\rm BH} = 892\,{\rm km\,s^{-1}} \times$$

$$\left(\frac{a}{1\,{\rm AU}}\right)^{-1/2} \left(\frac{M_{bin}}{8 M_\odot}\right)^{1/3} \left(\frac{M_{BH}}{3.7 \times 10^6\,M_\odot}\right)^{1/6} \quad (1)$$

To reproduce the high HVS velocities we consider binaries with $a < 0.95$ AU. These are tidally disrupted at $r_t < 3.8 \times 10^{-4}$ pc and eject an unbound HVS with $v_{\rm BH} \gtrsim 920\,{\rm km\,s^{-1}}$ which could be observed as an HVS with velocity $> 450\,km\,s^{-1}$ at 55 kpc from the GC, given estimated Galactic potential difference between the cen-

ter and 55 kpc of $v_{55} \sim 800\,{\rm km\,s^{-1}}$ (Carlberg & Innanen 1987)).

For the semi-major axis distribution of massive binary stars, which is strongly biased towards close binaries a large fraction of all binaries, $(f_{bin} \sim 0.3-0.9)$ have semi-major axis short enough ($\lesssim AU$; Garmany et al. 1980; Abt 1983; Kobulnicky & Fryer 2006) , such that the binary disruption by the MBH would lead to a ejection of HVS. Therefore given the ~ 100 HVSs inferred from observations one would require $\sim 330/(f_{bin}/0.3)$ binaries to be disrupted. This does not constrain the stellar population from which the binaries originate (most originate from the central $10\,pc$ of the GC where $\sim 10^4$ such binaries exist), but may constrain the number of captured stars (Perets et al. 2007). In each binary disruption the companions to the ejected stars are captured by the MBH. The capture semi-major axis distance to the MBH is linearly dependent on the semi-major axis of the original stellar binary (Hills 1991), which is $\lesssim 0.02$ pc for the companion of a HVS) and therefore $100-300$ such stars should be captured near the MBH during the last $\sim 10^8$yrs in this region. This is generally consistent with current observations of ~ 100 massive B stars at < 0.04 pc from the MBH, where the number of less massive (less luminous) B stars may be a few times larger[2].

Although less likely, the initial semi-major axis distribution of B MS binaries in the GC environment may behave like that of lower mass stars (Duquennoy & Mayor 1991). Most binaries with large semi-major axis would not survive for long in the central regions of the GC (< 10 pc; from which most disrupted binaries originate; see fig. 1), and so only the closer binaries (about half of the primordial population) survives. In this case the fraction of disrupted binaries which lead to ejection of HVSs (binaries closer than $\lesssim AU$) is ~ 0.16. Therefore we obtain a total number of $\sim 100/0.16 = 625$ stars captured by the MBH during the last $\sim 10^8$yrs. However, many of these captured stars would be captured at much larger distances than the companions of HVSs and would be distributed up to distances of $\sim pc$ from the MBH; i.e. the constrain we have is of ~ 625 B type stars (more likely a few times more, if both stars are captured, and also taking into account the larger impact parameter for wider binaries) in the central pc. This is still marginally consistent with current observations in this region, but might be excluded with future observations. We conclude that the scenario of HVS ejection from binary disruption is consistent with current observations of B stars in the GC given a binary distribution of B stars binaries similar to that observed in the solar neighborhood, and marginally consistent if the binary distribution is similar to that of lower mass stars in the solar neighborhood.

3. CONSTRAINTS FROM THE EVOLUTION OF BINARY SYSTEMS IN THE GALACTIC CENTER

Stellar evolution in binary systems can be very different than the evolution of isolated stars. In such systems the binary components may interact in many ways, whether through mass transfer, tidal forces, winds, radiation or other ways. Such interaction can considerably change the evolution of the stars and lead to unique characteristics of stars that are different or not even accessible to stars evolved in isolation. Some of these effects require long term evolution in binaries. Other effects

are related to the formation process of a binary system (e.g. stars in binary systems show lower average rotational velocities than single stars, irrespective of their age (Abt & Boonyarak 2004)). Observationally, several peculiar stellar populations are observed mostly or only in binaries (Abt 1983).

The different evolution of stars in binaries can be used for discriminating between ejection scenarios of HVSs and help to understand and predict their characteristics. Recently, two such discriminators have been suggested. The binary disruption scenario, by definition, involves the ejection of a single star which evolved in a binary. It was pointed out that binary components have lower average rotational velocities (Abt & Boonyarak 2004), and therefore HVSs from such a scenario should similarly be slow rotators (Hansen 2007). In the inspiraling IMBH scenario both single and binary stars could be ejected as HVSs. The later possibility of a binary HVS has been suggested as a unique signature of the IMBH inspiral scenario (Lu et al. 2007). In the following we generalize the use of binary evolution as a signature of HVSs ejection scenarios (and predictors for their nature) and suggest additional signatures. However, we also show that the dynamics of binaries in the GC usually make this type of signatures only weak signatures at most, and would probably require large statistics to be useful discriminators in most cases. Nevertheless, these may better constrain the characteristics of HVSs ejected from the GC and may help explain the asymmetric velocity distribution of observed HVSs.

We note that all of the arguments given below are predictors not only for the characteristics of HVSs, but also for stars observed close to the MBH, that were either formed close by (e.g. in the recently observed stellar disk; Paumard et al. (2006)) or captured through the binary disruption mechanism (Perets et al. 2007).

3.1. Binary survival in the Galactic center

Binaries may survive for a Hubble time unless destroyed due to stellar evolutionary processes (e.g. merger or disruption due to mass transfer or mass loss) or subjected to dynamical interactions. In dense environments the later possibility may play an important role in the evolution of binary systems. In such environments binaries (soft binaries; Heggie 1975) may gradually evaporate due to perturbations from encounters with other single stars if

$$|E|/m_{bin}\sigma^2 < 1, \qquad (2)$$

where $E = -Gm_1m_2/2a$ is the orbital energy of a binary with component masses m_1 and m_2 and separation a, $m_{bin} = m_1 + m_2$ is the binary mass and σ is the velocity dispersion of stars in the system. Due to the high velocity dispersions in the GC, all but the closest (contact) binaries are soft binaries. Hard close binaries can become harder due to interactions with other stars, i.e. become even closer. However the hardening changes the orbital energy of these binaries at a rate of less than ~20 percents per relaxation time for marginally hard binaries, and even less for harder binaries (see e.g. Eq. 8-113 in Binney & Tremaine 1987). This would only slightly change the distribution of periods of close binaries. Given the uncertainties in the distribution of binaries in the GC this effect is negligible and do not
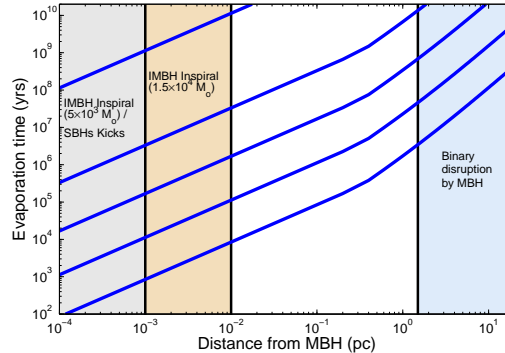

FIG. 1.— Evaporation time of binaries in the Galactic center for binaries with different semi major axis; 0.01 AU (contact binaries), 0.1 AU, 1 AU, 10 AU and 100 AU (from top to bottom). The shaded regions show the distance range from which most hypervelocity stars are ejected in the IMBH inspiral scenario (IMBH masses of $1.5 \times 10^4 M_\odot$ and $5 \times 10^3 M_\odot$;Sesana et al. (2007b)); the SBHs kick scenario (O'Leary & Loeb 2007); and the binary disruption scenario (Perets et al. 2007).

contribute much to the processes of binary evolution in the GC. Most of the binary population in the GC is in soft binaries. The evaporation time of such binaries is given by ((Binney & Tremaine 1987)

$$t_{evap} = \frac{m_{12}}{m} \frac{\sigma}{16\sqrt{\pi}\rho a \ln \Lambda}, \qquad (3)$$

where ρ is the stellar density, m is the typical mass of a star in this region and $\ln \Lambda$ is the Coulomb logarithm. In the GC σ is dependent on r; $\sigma \sim \sqrt{GM(<r)/r}$, where $M(>r)$ is the enclosed mass up to distance r from the MBH. Fig. 1 shows the evaporation time for binaries with different semi-major axis $(10^{-2} - 10^2 \, AU)$ in the central regions in the GC, taking $\rho(r) = \rho_0(r/r_0)^{-\alpha}$, where $r_0 = 0.4$ pc, $\rho_0 = 1.2 \times 10^6 M_\odot \mathrm{pc}^{-3}$, $\alpha = 1.4$ for $r < r_0$ and $\alpha = 2$ for $r > r_0$(Genzel et al. 2003). The binary mass ratio is assumed to be 1 $(m_{12} = 2m)$.

Typical low mass $(< 3M_\odot)$ binaries have a log normal distribution of semi-major axis centered around $\sim 30 \, AU$ (Duquennoy & Mayor 1991). As can be clearly seen in fig. 1 most such binaries can not survive for long close to the MBH. Many of the peculiar properties of stars evolved in binaries are due to their long term evolution in such systems (Abt 1983). Since binaries close to the MBH are disrupted in very short time scales, the component stars in these binaries would become single stars, and effectively evolve as isolated stars. Consequently, peculiar stellar populations that require long term evolution in binaries are not expected to form in these regions. As discussed earlier, the scenarios of HVSs ejection by SBHs or by an IMBH are most efficient at close distances of $\sim 0.001 - 0.01$ pc from the MBH, and therefore most HVSs are ejected from these region in these scenarios (O'Leary & Loeb 2007; Sesana et al. 2007b). At such distances from the MBH the velocity dispersion is of few$\times 10^2 - 10^3 \, km \, s^{-1}$, and even the closest binaries are soft and would be disrupted in less than 10^7yrs (see fig. 1), i.e. shorter than the main sequence lifetimes of most stars. Consequently, hypervelocity binaries that were suggested as a possible signature of the IMBH inspiral scenario (Lu et al. 2007) and peculiar stellar populations evolved and observed mainly in binaries

are not expected to be ejected as HVSs in these scenarios (see also Löckmann & Baumgardt (2007)). Other stellar populations include for example subdwarf B (sdB) stars (Maxted et al. (2001); Han et al. (2003), Am stars (see also Hansen (2007)) and BY Dra stars (see Abt (1983) for a review).

In the binary disruption scenario for ejection of HVSs a different picture arises. In this case most binaries disrupted by the MBH come from much larger distances from the MBH ($\gtrsim 2\,pc$; Perets et al. (2007)) than HVSs ejected in the SBHs kick or IMBH inspiral scenarios. At these distances binaries could survive longer (fig. 1). However, a HVS is ejected following the disruption of the binary, destroying the possible progenitor of any binary evolved peculiar star. Consequently, only stars that already evolved in a binary to become peculiar prior to the disruption of the binary could be ejected as peculiar type HVSs. Unfortunately the lifetime of many peculiar stars at this phase are usually much shorter than their lifetime on the MS (e.g. the lifetime of sdB stars are of the order of a $1-2 \times 10^8$yrs (Dorman et al. 1993), where their progenitor MS lifetimes could be a few Gyrs) and therefore fine tuning would be required for the ejection of HVSs in this case (i.e. they need to be ejected in the short time after they become peculiar, and before they end their life at this phase) and they would be rare. Nevertheless, if observed, they are expected to be single stars, which would be a strong signature of their binary disruption origin, since such stellar populations are expected to be and usually observed as binary stars.

Some stellar populations do not exist in binaries, or exist only in long period binaries. In the binary disruption scenario, such stellar populations are not (or rarely) expected to be ejected as HVSs. For example, Be type stars and A4-F2 type stars are usually observed with large semi major axis, and their binary fraction at smaller semi-major axis ($<\sim AU$) is low (Abt 1983; Abt & Cardona 1984). Statistics of this type of stars in HVSs observations (or of stars very close to the MBH in the GC, where they could have been captured in the binary disruption mechanism; see e.g. Gould & Quillen 2003; Perets et al. 2007), could give a measure of this possible signature for the HVSs origin from binary disruptions.

3.2. *Rotational velocities of hypervelocity stars*

Recently it was suggested that the rotational velocity of HVSs can serve as a signature for their origin (Hansen 2007). Observations show that field A and B type MS stars that evolve in binaries have lower average rotational velocities than isolated stars (Abt et al. 2002; Abt & Boonyarak 2004). If HVSs origin is from the binary disruption scenario, they are expected to form in binaries and therefore be slower rotators on average. Lower rotational velocities have been observed even for relatively young MS stars in binaries, suggesting that the low rotations are related to their formation in a binary and are not a consequence of their later evolution in that system (Abt & Boonyarak 2004). Consequently stars formed in binaries should show this signature even if their binaries have been disrupted in a short time.

We point out that the rotational velocity distribution of stars both isolated and in binaries is very wide spread (see fig. 2), and therefore some statistics are required to
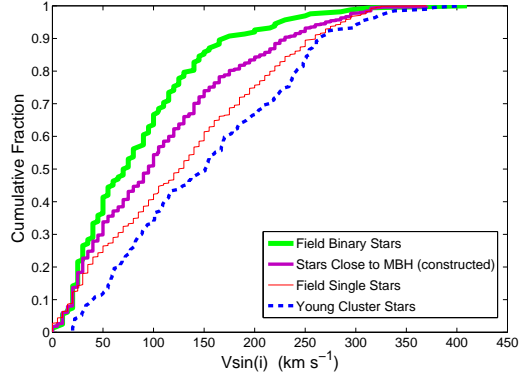

FIG. 2.— Cumulative distribution of the rotational velocities of massive B stars of different environments or populations. From top to bottom, field stars in binaries (Abt & Boonyarak (2004); thick solid line), constructed distribution close to the MBH (see text; intermediate solid line), isolated field stars (Abt et al. (2002); thin solid line) and young cluster stars (h and χ Persei, Strom et al. (2005); dashed line).

test this signature and the rotational velocity of a single star can not pinpoints to its origin as a single or a binary star (many of the stars formed in isolation are quite slow rotators (Abt & Boonyarak 2004), where as some of the binary evolved stars are very fast rotators). Using a Kolmogorov-Smirnov test we find out that $\gtrsim 25$ B MS HVSs are required, on average, to be able to differentiate between these distributions with a $\geq 95\%$confidence level, if all these HVSs are taken from the same distribution (either all evolved in binaries or all evolved in isolation).

Binaries formed close to the MBH in the GC are soft binaries and would shortly after be disrupted due to perturbing encounters with other stars. Consequently the binary components, now single stars, should also have lower rotational velocities, on average, similar to other stars formed in binaries. Since the binary fractions of stars are high (e.g. $> 70\%$ for B stars in young clusters; Kobulnicky & Fryer 2006; Kouwenhoven et al. 2007), many, probably most, of the A and B MS stars in the GC are expected to have formed in binaries as slow rotators, and later on become single stars. If HVSs were ejected due to the SBH or IMBH kick scenarios, most of them are therefore expected to be relatively slower rotators. Still, a non-negligible fraction of the stars are formed as isolated stars and possibly be faster rotators.

We can construct the rotational velocity distribution of the currently single stars populations close to the MBH (< 0.01pc). The stellar population in this region is composed of single stars formed in isolation and of single stars originally formed in binaries that have evaporated (with the appropriate fractions). The constructed rotational velocities distribution is the combination of the single stars and binary stars rotational velocities with the appropriate weights, that depend on the binary fraction in the population. To be conservative we take a lower limit on the initial binary fraction of $\sim 35\%$ (Abt 1983) where one should recall that each evaporated binary contributes two stars to the combined single stars population. In other words, any star chosen from our constructed rotational velocities distribution in the GC

has a $35 \cdot 2/(35 \cdot 2 + 65) = 0.51$ probability to originally form in a binary and therefore have a rotational velocity chosen from the binary stars distribution, although it is currently a single star. Again using a Kolmogorov-Smirnov test we find out that $\gtrsim 100$ B MS HVSs are required, on average, to be able to differentiate between these distributions with a $\geq 95\%$confidence level, if all these HVSs are taken from the same distribution (either all from the constructed distribution for the stellar population in the close environment of the MBH, or all evolved in binaries). Given the small number of HVSs observed and inferred to exist, such a signature for the HVSs origin is unfortunately quite weak (even weaker if a higher binary fraction is assumed).

Recently Strom et al. (2005) and Wolff et al. (2007) have shown that the rotational velocity distribution in denser environments lack the cohort of slow rotators, thus showing very different rotational velocity distribution than field stars. Given these observations and our poor knowledge on the star formation environments in the GC (both close to the MBH and further out), it would be difficult to use the rotational velocities of HVSs as a tracer for their ejection scenario. If the B MS stars close to the MBH have formed in a dense environment (as would be expected if they formed, e.g. in a stellar disk close to the MBH; Paumard et al. 2006) they are expected to be relatively fast rotators, i.e. opposite to the expected distribution as discussed above. We conclude that the rotational velocities of A and B MS HVSs are strongly dependent on the formation environment of these stars, but are most likely not good tracers for the ejection scenario of HVSs. Data on the rotational velocity distribution of stars close to the MBH and further away, may be an important clue for our understanding of their ejection mechanism, but even in that case too large statistics may be required for them to be used as a signature for the HVSs ejection scenario.

3.3. *On the asymmetric velocity distribution of observed hypervelocity stars*

Current observation of HVSs detect B type stars of limited magnitude. Such HVSs could either be MS B stars ($3 - 4\,M_\odot$; possibly blue stragglers) or hot BHB stars. The velocity distribution of HVSs shows a marked asymmetry between HVSs with much more HVSs with positive Galactocentric radial velocities than HVSs with negative ones (Brown et al. 2007b). This was suggested to infer that the observed HVSs have short lifetimes, and therefore bound HVSs are too short lived to be observed returning with negative radial velocities (Brown et al. 2007b; Kollmeier & Gould 2007; Svensson et al. 2007).

If HVSs are ejected continuously, such as in the ejection scenarios of the binary disruption by a MBH or scattering by SBHs, then bound HVSs ejected at earlier times could now be observed returning with negative radial velocities. In this cases no asymmetry in the HVSs velocity distribution should be observed (up to the escape velocity from the galaxy, above which no returning stars are expected at any time). Consequently the observations of asymmetry may raise a grave problem for these scenarios, unless there is a special physical reason for ejecting stars with short lifetimes. One explanation could be related to the survival probability of binaries in the GC.

Hot BHB stars have been suggested to form through

evolution in binaries and may have high binary fraction, similar to sdB stars (Peterson & Green 2002; Peterson et al. 2002). If this is the case, then the fast evaporation of binaries close to the MBH in the GC would exclude the formation of such stars (as well as sdB stars) and no such BHB HVS would be ejected in the SBHs kick or IMBH inspiral scenarios (see discussion in section 3.1). In this case Hot BHB stars would be very rare in the population of HVSs, and therefore all or most of the observed HVSs are B MS stars, that naturally have short lifetimes consistent with the asymmetric velocity distribution of observed HVSs. Alternatively, even if some of the HVSs are hot BHB stars (e.g. from the binary disruption scenario, see section 3.1), they had to be ejected only after they evolved to this stage, and therefore their propagation time as HVSs is limited to their lifetime at this phase, which is short (a few 10^8 yrs) and comparable to that of MS B stars. In both cases, an asymmetric velocity distribution of the HVSs would be expected.

HVSs could also be blue straggler stars (which would possibly give them longer propagation times, and therefore different observable velocity asymmetry). In this case the same arguments could be introduced as for the hot BHB stars. Since the evolution of blue stragglers is also through mass transfer in binaries (or stellar collisions, however, this would not happen for an ejected star), and most, if not all of the field blue stragglers are in binaries (Carney et al. 2001; note, however, that these refer to lower mass blue stragglers), we may expect to see only blue straggler HVSs that have been ejected already after they evolved to this phase. Such stars are practically indistinguishable from regular MS stars, and their lifetime at this stage is as short.

Another possibility for explaining HVSs velocity asymmetry is the case of a limited time-span for the ejection of HVSs, such as expected during an IMBH inspiral in the GC; i.e. a short lived discrete event, and not long lived continuous process such as discussed above. In this case stars are expected to be ejected only during the limited and relatively short timescale at which the IMBH could eject HVSs (unless several such inspiral events happened). Such timescale could be as large as 10^8yrs (Löckmann & Baumgardt 2007), which could marginally fit the observed ejection time span of the unbound HVSs (fig. 8 in Brown et al. 2007b)[3].

Recently the possibility of rare massive binary encounter in dense young clusters (Gvaramadze et al. 2007) have been suggested for ejecting HVSs. Such a process is also a continuous process which should have similarly lead to a symmetric velocity distribution. However, in this scenario mostly massive stars (and hence short lifetimes) are expected to be ejected, which could explain the lack or high velocity returning stars. However, it is not at all clear whether the necessary conditions in such young clusters exist, and whether the frequency of such rare strong encounters could explain the observed population of HVSs (and especially unbound HVSs) to begin with (see Perets 2008 for a short discussion on this).

We conclude that the currently observed B type HVSs

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[3] Notice, however, that scattering of stars by massive perturbers such as giant molecular clouds and clumps could shorten the inspiral time of the IMBH considerably (Perets & Alexander 2007).

are most likely MS B stars, and suggest that hot BHB HVSs could only be produced in the binary disruption scenario. However, even in the later scenario these are not expected to be frequent.

4. SUMMARY

In this study we have explored some dynamical and evolutionary constraints on the nature and origin of HVSs and of the stellar population in the GC. Hypervelocity stars are thought to be ejected through dynamical interactions near the MBH in the GC. Three scenarios have been suggested for their ejection; a disruption of a binary star by the MBH, scattering by an intermediate mass BH which inspirals to the MBH or scattering by stellar BHs in the close region of the MBH. In the binary disruption scenario HVSs originate only from binaries, where most of them evolved far from the MBH ($> 2\,pc$). In the scattering scenarios by an intermediate mass or stellar BHs most HVSs are single stars scattered from a close region near the MBH (< 0.01 pc from it). Given the differences between them, the ejection scenarios of HVSs are expected to involve different stellar populations in the GC. We have used dynamical and evolutionary arguments together with current observations regarding the stellar population in the GC to constrain the nature and origin of HVSs. We have shown that the IMBH inspiral scenario requires too many main sequence B stars to exist close to the MBH (< 0.01 pc). Scattering by SBHs are also not likely to be consistent with the observed population of B stars in the Galactic center, although this scenario can still be compatible with observations under extreme conditions. The binary disruption scenario is still consistent with current observations.

Due to the conditions close to the MBH most binary star systems are not expected to survive for long in this region. Consequently unique stellar populations that require a long evolution in a binary, such as subdwarf (and possibly hot blue horizontal branch) B stars, blue stragglers, Am stars and other populations are not expected to be ejected as HVSs in the SBHs kicks or IMBH inspiral scenarios. In the binary disruption scenarios the binaries involved originate much further from the MBH where they could survive longer, and therefore HVSs of these unique stellar population are not excluded, although their rates might be quenched because of their shortened evolution in the binary systems. Conversely, stellar populations that are not frequently observed in close binaries such as required in the binary disruption scenario (e.g. Be stars, A4-F2 type stars) are not expected to be ejected as HVSs, or to be captured close to the MBH in this case, but they can still possibly be ejected in the SBHs kicks scenarios. We also show that these arguments suggest that signatures for HVSs origin such as hypervelocity binaries and slow rotating HVSs may be much weaker than expected and may require large statistics.

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